Thermal analysis of ductile iron in thin walled casting

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Abstract
Hypereutectic ductile iron was cast in self hardening moulding sand to produce castings with the shape of Archimedes spirals and with wall thickness of 1, 2 and 3 mm. Inmould technique was used to produce thin wall ductile iron (TWDI). In this work it has been carried out thermal analysis in spiral with 3 mm wall thickness. The present work provides results of thermal analysis, that are initial temperature of metal in mould cavity, velocity of metal stream as well as solidification time. Measurement of temperature shows that there is essential its drop during filling of mould cavity and amounts 230 °C for distance 700 mm from the beginning of spiral. On the basic of first derivative of temperature versus time characteristic solidification points were distinguish, namely solidification of primary graphite, austenite dendrite and eutectic. Experimental measurements of temperature drop during filling of mould cavity along with microscopic examinations of castings structure can be used to verify computer modeling and simulation of fluid flow and thermal field in TWDI.

Keywords: Thermal analysis, Thin wall castings, Archimedes spiral

1. Introduction
Cast iron is sensitive on cooling rate what in unfavorable from structure viewpoint and leads to inhomogeneity of mechanical properties. It is especially important if the aim is to produce castings with high strength and plasticity. Thin wall ductile iron (TWDI) characterize high cooling rate at the beginning of eutectic solidification (for 3 mm wall thickness cooling rate amounts about 30-60 °C/s). In works [1,2] it has been proved that pouring temperature (in mould represented by initial temperature of liquid metal) and also its further drop as a result of intensive heat transfer mould/flooding metal (about 1000 Wm⁻²K⁻¹) are responsible for gradient structure which is represented by graphite nodule count, ferrite and cementite fraction. In literature there are available analytical relationships for critical distance from the beginning of ingate above which there are chills present in castings [1,2]. Thin wall thickness causes technological problems connected with castability. TWDI demand from gating system to be possible simple with minimum turbulence of flooding metal stream in order to avoid temperature drop, oxidation, gas and inclusions entrapment from slag and mould [5]. In literature dealing with TWDI e.g. [3-5] horizontal and vertical plate-shaped castings were analyzed. In case of horizontal castings it has been observed a lot of defects caused by insufficient: feeding and metal castability. Moulds for vertical plate-shaped castings showed better filling conditions that is elimination of high temperature gradient of liquid metal as well as break of stream continuity [5]. In literature there are limited experimental data dealing with possible use of thermal analysis in TWDI [6,7]. These works are limited to basic research of TWDI with different wall thickness plate-shaped castings with small length [5-7]. The aim of this work is thermal analysis of ductile iron in mould of Archimedes spiral cavity and 1500 mm length.
2. Methodology

Test melt was made in electric induction furnace. The raw materials were Sorelmetal, commercially pure silicon, and steel scrap. The metal was preheated at 1500°C and then poured into the mould. It has been used self hardening moulding sand, made of silica sand (100 wt. part), resin Kalharz U404 (Huttenes Albertus) (1.3 wt. part.) and activator 100 T3 (0.5 wt. part).

Casting mould was equipped with reaction chamber and mixing basin. In reaction chamber mixture of 53 grams of spheroidizer* and 30 grams of inoculant were placed in. In mixing basin secondary inoculation was made by means of 5 grams of inoculant. After filling the mixing basin, a graphite plug was removed allowing metal flow into the down-gate and then into mould cavity reproducing Archimedes spiral with 1500 mm length and 1x15, 2x15 and 3x15 mm sections, respectively (Fig.1a). The chemical analysis showed that cast iron was of hypereutectic composition.

Temperature of metal in mould cavity with a shape of Archimedes spiral and with wall thickness of 3 mm was estimated using unsheathed thermoelements wires in regular 100 mm distances. Scheme of temperature measurement is shown in Fig. 1b.

Flooding metal stream in mould cavity closes circuit of unsheathed thermoelements wires (K type) with thickness of 0.2 mm which are connected with digital data acquisition system AGILENT 34970 A. Temperature was recorded with time step of 0.03 s. In Fig. 2 it is shown picture of Archimedes spiral with wall thickness of 1, 2 and 3 mm.

3. Results

In table 1 it is presented results of thermal analysis that are initial temperature of metal in mould cavity (Ti), velocity of metal stream as well as solidification time. Castability of tested cast iron was as follows: 220 mm, 725 mm and 1000 mm for spirals with wall thickness 1, 2 and 3 mm, respectively (Fig. 2).

<table>
<thead>
<tr>
<th>Distance from the beginning of spiral, mm</th>
<th>Initial temperature of metal in mould cavity T, °C</th>
<th>Velocity of metal stream, m/s</th>
<th>Solidification time, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down-gate</td>
<td>1360</td>
<td>-</td>
<td>141.1</td>
</tr>
<tr>
<td>100</td>
<td>1270</td>
<td>1.41</td>
<td>12.9</td>
</tr>
<tr>
<td>200</td>
<td>1244</td>
<td>2.08</td>
<td>11.6</td>
</tr>
<tr>
<td>300</td>
<td>1219</td>
<td>0.89</td>
<td>10.6</td>
</tr>
<tr>
<td>400</td>
<td>1213</td>
<td>0.70</td>
<td>10.3</td>
</tr>
<tr>
<td>500</td>
<td>1190</td>
<td>0.60</td>
<td>9.8</td>
</tr>
<tr>
<td>600</td>
<td>1163</td>
<td>0.56</td>
<td>8.7</td>
</tr>
<tr>
<td>700</td>
<td>1130</td>
<td>0.55</td>
<td>7.5</td>
</tr>
<tr>
<td>800</td>
<td>1060</td>
<td>0.56</td>
<td>-</td>
</tr>
</tbody>
</table>

Thermal analysis show that temperature drop which is graphically presented in Fig. 3a between down-gate and distance 700 mm from the beginning of spiral amounts 230 °C. It is worth nothing that progress of temperature drop is qualitatively consistent with analytical equation given in works [1,2].

* Sferoidizer Elmag 5800 (44-48 % Si, 5.5-6.2 % Mg, 0.8-1.2 RE, 1.0 % max. Al) and inoculant FoundrySil (73-78 % Si, 0.75-1.25 % Ca, 0.75-1.25 % Ba, 0.75-1.25 % Al) are commercial products of Elkem company (Norway).
Fig. 3. Initial temperature of metal in mould cavity ($T_i$) and solidification time as a function of spiral length (a), velocity of metal stream versus spiral length (b)

Fig. 4. Cooling curves of cast iron recorded at different distance (x) from the beginning of spiral

Fig. 5. Cooling curve and its first derivative at distance 100 mm from the beginning of spiral

Metal stream during filling of mould cavity decreases its temperature and velocity (Fig 3). Analysis of cooling curves and its first derivatives show that as distance from beginning of spiral increases solidification time decreases (Fig. 3a) which progress is analogies to temperature drop ($T_i = f(x)$). Solidification time of cast iron was estimated as a difference between solidification of primary graphite ($T_1$) and the end of solidification ($T_4$) as it is shown in Fig. 5. Solidification time in down-gate is in order of magnitude higher than in casting with 3 mm wall thickness. In Fig. 4 there are presented curves obtained at different distance from the beginning of spiral. At the beginning of cooling curves one can observe disturbances as a result of moving liquid metal during filling of the mould. Time of this noise is proportional to filling time at a given measurement point. Fig. 5 shows cooling curve and its first derivative at distance 100 mm from the beginning of spiral. First derivative can be helpful in determinate characteristic points. It is well known description of cooling curves for a typical cast iron with different chemical composition and thus with different carbon equivalent. In this case we have hypereutectic cast iron and at the beginning of solidification the following characteristic points can be distinguished: solidification of primary graphite ($T_1$), austenite dendrite ($T_2$) and eutectic ($T_3$). This atypical sequence of solidification for hypereutectic cast iron is in accordance with microstructures observations. In Fig. 6 there is shown microstructure taken from 100 mm from the beginning of spiral with visible primary graphite, traces from primary austenite dendrites and eutectic graphite.
It is typical phenomenon \[6-9\] for thin wall ductile iron castings with hypereutectic composition, where presence of primary graphite facilitate nucleation of austenite in dendritic form. In consequence microstructure is of dendritic morphology of austenite, typical for hypoeutectic composition as well as in the form of envelope around graphite nodule.

Temperature measurements of liquid metal in mould cavity are of high importance due to its strong influence on chills in cast iron \[10\]. Experimental measurements of temperature drop during filling of mould cavity along with microscopic examinations of castings structure \[1, 11\] can be used to verify computer modeling and simulation of TWDI fluid flow. It is especially important due to gradient structure of TWDI manifested in inhomogeneity of castings structure and thus properties.

4. Conclusions

In this work it has been carried out thermal analysis of flooding metal stream in mould cavity with 3 mm wall thickness. Measurement of temperature show that there is essential its drop during filling of mould cavity and amounts 230 °C for distance 700 mm from the beginning of spiral. Progress of temperature drop is qualitatively in accordance with theoretical predictions given in works \[1,2\]. It has been proved that on the basic on first derivative of temperature versus time characteristic solidification points can be distinguish, namely solidification of primary graphite, austenite dendrite and eutectic. Temperature drop of flooding metal stream in mould cavity causes decrease in solidification time of cast iron and its character is in accordance with temperature drop \(T = f(x)\). The foregoing investigations provide experimental data which are essential in computer modeling and simulation processes of metal flow and solidification of TWDI.

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References